Modelling and simulation tool for off-grid PV-hydrogen energy system

Onwe, Christian A.; Rodley, David; Reynolds, Stephen

Published in:
International Journal of Sustainable Energy

DOI:
10.1080/14786451.2019.1617711

Publication date:
2020

Modelling and simulation Tool for Off-Grid PV-Hydrogen Energy System

Christian A. Onwe, David Rodley, Stephen Reynolds

Department of Electronic Engineering and Physics, University of Dundee United Kingdom

Dundee University Centre for Renewable Energy (DUCRE)

Corresponding author: Christian A. Onwe, christianonwe@gmail.com

Abstract

This paper introduces a user-oriented software tool for simulation of a solar energy-based hydrogen production system. The developed tool goes beyond the realm of electric load and includes a hydrogen cooking load facility, as an efficient means of utilising the hydrogen produced. A model rural household in Nigeria has been used to evaluate the tool. It was found that a 2.42 kW solar photovoltaic module, 0.6 kW electrolyser and 3.7 kWh battery would be enough to provide steady 24-hour power for a typically modest daily energy demand of 2.2 kWh. A prospect of harnessing an excess energy on clear weather conditions and utilising it to produce hydrogen is discussed. In the results, the excess energy realised was used in a H_2-cooker to partly meet the estimated 1.9 kWh/day cooking demand of the household over a simulated year period.

Keywords: *Renewable energy, Hydrogen, Electrolyser, H_2-cooker, SOHYSIMO, Battery.*

1.0 Introduction

Renewable energy systems are limited by the intermittent and somewhat unpredictable nature of the weather. This inherent variability means that excess power could sometimes be generated by these systems, and this requires that a designer or engineer carry out a detailed study of the site of interest to ascertain the optimal energy requirement prior to the actual implementation of a project. To do this, a simulation tool is often employed, which can be selected based on specific need. This paper introduces a new user-oriented software model for simulation of a solar – hydrogen energy system that goes beyond the realm of electrical load to include an auxiliary thermal load in the form of a hydrogen cooking facility.

The following are contributions made in the current tool;

The developed tool introduces a new loading facility which goes beyond the realm of electrical load and include a hydrogen cooking load.

Operating and maintenance cost is an important factor in every renewable energy-based project, a novel method for calculating this has been developed and incorporated into the model to obtain an optimal design of a solar PV-hydrogen project.

Energy storage is an important cost factor in renewable energy systems, and a new method for determining the days of autonomy (DoA) required from the battery storage has been implemented.

The optimisation process includes an approach whereby the battery days of autonomy and its depth of discharge are considered. The optimisation process has two stages, which allows the user to make informed decisions; (1) whether to fully satisfy an annual cooking load, (2) or to satisfy part of the cooking load, based on the amount of excess energy generated.

SOHYSIMO has a facility that computes the electrolyser efficiency based on size (electrolyser capacity).

1.1 Hydrogen as a cooking fuel

Recent advances in renewable technologies have proffered various energy provision opportunities, especially in rural unserved areas. Off-grid renewable energy systems may be most cost-competitive when provided to isolated remote areas with little prospect of grid connection. Integration of a viable energy storage system is essential to provide management of supply and demand side issues. Energy can be stored in batteries, or via hydrogen, supercapacitors, flywheels and so on. In this paper, the storage media of most interest are batteries and hydrogen.

To make the energy system more reliable in terms of availability of supply, it can be connected to an electrolyser such that the excess electrical energy generated by the system during periods of high energy resource can be utilised to split water into its basic constituents and the hydrogen captured. Traditionally, batteries are used in renewable energy systems to maintain a dynamic balance of supply and demand. In this study, excess system energy is used to generate hydrogen, and this is proposed to be used to meet cooking demand.

At 142MJ/kg hydrogen has the highest energy content per unit mass compared to any fuel. The conversion of hydrogen to heat is a very energy-efficient process, and the use of hydrogen for domestic heating has attracted important interest in recent years. There is a potential for hydrogen as a safe efficient fuel source in the domestic setting and as a long-term replacement for natural gas (Mark et al. 2015). There are few reported works on the use of hydrogen as an alternative off-grid cooking fuel. In this paper, a model for a basic off-grid electro-thermal system is described.

Previous researchers have reported important numerical and experimental studies on the utilisation of renewable generated hydrogen for household cooking. (Topriska et al. 2015) describes a numerical model developed in TRNSYS (Transient System Simulation Tool) for large-scale solar powered hydrogen production for domestic cooking in Jamaica. Their model took a holistic approach in developing a cooking demand profile by source, but most rural dwellers do not use LPG as they describe and this model may be more applicable to urban dwellers than the rural. In addition, their model did not consider the use of excess energy that could be generated from the renewable energy system, rather it was based on utilising all energy generated to produce hydrogen without an integration of another storage medium. This has important cost implications, as currently it would not be practical to install a solar plant for the sole purpose of generating hydrogen. In other reported works, a possible application of hydrogen for domestic cooking has also been proposed (Yilanci, Dincer, and Ozturk, 2009; Barbir 2005).

1.2 Brief literature

Considerable previous work done over the past decade has used Excel VBA as a platform for development of software tools for off-grid renewable energy systems. Ali et al proposed a tool for sizing model of RE system components of a photovoltaic power system in Iraq (Ali, and Salih 2013). (Vladimir, and Suchanek 2014) developed a comprehensive software model they called Expert System, which can be used to simulate and optimise an off-grid hybrid renewable power system comprising solar, wind and battery storage. (Kuo et al. 2012) describes the use of VBA for development of a tool which may be used to assess system operating conditions and characteristic behaviour of a solar and wind energy system. (Mhalas et al.2013) demonstrated a modelling tool for visual energy performance assessment and decision support for dwellings. In the literature only (Diaf et al. 2007) appears to address the issue of properly balancing the energy supply, but their model did not seem to include a system by which the excess supply can be effectively utilised once the batteries are fully charged. Evidently, there is no energy tool that addresses all issues related to integrating renewable technologies (Connolly 2010).

1.3 Overview of the software tool

'**SOHYSIMO**' is an acronym for Solar Hydrogen Simulation Model and is a DC power simulation software optimised for low power consuming households, especially off-grid rural dwellers. The software has a facility which can help a designer to make an informed decision on how hydrogen produced by solar PV- derived electrolysis of water can best be utilised. The model also allows the system to be deliberately oversized electrically in order to satisfy both the electric and thermal load. SOHYSIMO is a prototype modelling tool and as such has used a simplified demand model. This will be refined in future work. The choice of Excel VBA as a platform is primarily based on the widespread availability of Microsoft software. The tool has been validated using different methods, including testing the tool against two prominent software models – HOMER and iHOGA, and comparing the tool's simulation outputs with measured data obtained from an existing renewable energy system. Details about these and other information regarding the models' simulation and optimisation architecture can be found in (Onwe 2017).

In the RES optimisation process, an input of data for example, the number of PV panels, the battery bank, etc can be used to represent the decision variables. The objective function can be expressed using a mathematical equation that relates these decision variables. It could be represented in form of minimising the cost per kWh of the hybrid RE system components including installation and maintenance costs, or maximising the available energy resources to satisfy the load demand. The constraints can be one or several factors imposed on the system using inequalities as a requirement set out as conditions that must be satisfied.

In this study, optimisation is achieved by minimising the cost per kW of the total system capacity that can satisfy a required daily load demand over the lifetime of the project. The optimisation algorithm is implemented in SOHYSIMO as illustrated below;

$$minimise\ f(\frac{Cost}{kW}) = f(PV(kW)) + f(PBatt(kW))$$ *(Equation 1)*

$$subject\ to$$

$$P_{pv} \geq P_{load} * 1.09$$

$$P_{batt} \geq P_{load} * (\frac{\frac{COUNTIF(Ppv,<3)}{24}}{52} * DoD)/1.9$$

$$P_{pv} \geq P_{batt} * 1.16,$$

$$P_{batt} \geq P_{load},$$

$$P_{pv} + P_{batt} \geq P_{load}$$

$$f(PV(kW)) = P_{pv} * CostPv,$$ *(Equation 2)*

$$f(PBatt(kW)) = P_{batt} * CostPbatt$$ *(Equation 3)*

$$where\ P_{pv} = PV\ output\ power, = P_{batt} = battery\ capacity,$$

$$CostPbatt = battery\ capital\ cost, CostPv = PV\ capital\ cost, P_{load} = load\ power$$

Cost calculations for all system components (Net present cost and levelised cost of energy) can be determined by entering the costs (capital, operating and maintenance (O&M) and auxiliary components) of individual system components of the solar-hydrogen power system. The tool uses the following formulas to calculate the Net Present Cost and levelised cost of energy (LCOE) of the Solar based hydrogen system;

$$NPC = \frac{Tot_{AnnC}}{CRF\ (interest,N)}$$ (*Equation 4)*

LCOE = $[\{\sum_{n=1}^{n=25} \frac{(Capex+O\&M)}{\sum kWh}\} * CRF]$ *(Equation 5)*

Where CRF = $\sum_{n=25} \frac{interest\ rate * (1+interest\ rate)^n}{[(1+interest\ rate)^n - 1]}$ *(Equation 6)*

$$Tot_{AnnC} = Total\ Annualised\ cost\ of\ system$$

n = time, in years

Capex = capital expenditure

O & M = operation and maintenance cost entered by the user

For cost optimisation, operating and maintenance cost is an important component, a novel method has been developed, which can be used to compute the annualised operating and maintenance cost over the lifetime of the project as illustrated in **equation 7**;

$$O\ \&\ M_{Life} = \left\{\frac{P_{life}}{Comp_{life}}\right\} * \left\{\frac{Comp_{cost}}{P_{life}}\right\} + OM_e \qquad \textit{(Equation 7)}$$

Where, $O\ \&\ M_{Life} = Lifetime\ Operating\ and\ Maintenance\ cost$

$$P_{life} = Project\ lifetime$$

$$Comp_{life} = system\ component\ lifetime$$

$$Comp_{cost} = cost\ of\ system\ component$$

$$OM_e = Operating\ and\ maintenance\ entered\ by\ user$$

The tool uses the following algorithm to facilitate hydrogen cooking optimisation H_2Cooker > (P_{pv} - P_{load})*(kWh/day)*0.2

In principle, the power output of the solar PV can be calculated as follows;

$$Ppv = \left(\frac{I_t}{I_{stc}}\right) * PV\ rated\ power\ (kW) * Derate\ factor\ (\%) \qquad \textit{(Equation 8)}$$

where; $Ppv = PV\ power$, I_t = incident solar radiation (kW/m^2) on the PV array at time t, I_{stc} = solar radiation in kW/m^2 at standard test conditions.

The equation used for PV power calculations of the software tool developed in this study is based on **equation 8.** De-rate factor represents the anticipated losses due to dirt or ageing of the PV panel.

A user may wish to select the option to model temperature effects, in that case the following formula is used to compute (estimate), thus;

$$T_C = T_A + \left(\frac{NOCT-20}{0.8}\right)\left(1 - \frac{\eta_c}{0.9}\right) \qquad \textit{(Equation 9)}$$

$$T_C = Cell\ temperature, T_A = Ambient\ temperature, NOCT = nominal\ operating\ cell\ temperature, \eta_c = cell\ efficiency.$$

Then PV power can be obtained as;

$Ppv = \left(\frac{I_t}{I_{stc}}\right)\left[1 + \alpha_p\left(\mathrm{T_c} - \mathrm{T_{c\,(STC)}}\right)\right] * PV\ rated\ power\ (kW) * \mathrm{DF}\ (\%)$
(Equation 10)

Where, $\alpha_p = temperature\ coefficient\ of\ power$

$$T_{c\,(STC)} = temperature\ at\ standard\ test\ conditions$$

$$DF = Derate\ factor$$

A user may need to enter values for these ($\alpha_p, T_{c\,(STC)}, \mathrm{T_c}$) in order to model the temperature effects. Also, for optimum power production a user may need to enter the slope or tilt angle as desired (in future version of this tool, a default value for this based on the latitude entered will be made available). SOHYSIMO utilises this to modify the solar irradiation based on tilt based on the following equations;

$\alpha = 90 - \emptyset + \delta$ *(Equation 11)*

Where

$\alpha = Angle\ of\ elevation, \emptyset = location\ latitude, \delta = declination\ angle = 23.5^o$

Then sum of angle of elevation and module tilt angle gives;

$Sum = \alpha + \beta$ *(Equation 12)*

Where $\beta = module\ tilt\ angle\ (to\ be\ entered\ by\ the\ user)$

Therefore, by combining equations 41 and 42 we obtain the panel transposition factor as follows;

$Transposition\ factor = Sin\left[\frac{Sum}{\alpha}\right]$ *(Equation 13)*

The battery model developed in this study was designed such that a user has the choice of adopting a load following method, and to charge the battery when the PV power exceeds load demand. When battery has attained a full state of charge, the remaining power from the PV will then be sent to electrolyser, the surplus power will then become excess power. The equation used to model the dynamics of the power delivery is as follows;

The battery bank capacity ($Batt_{cap}$) is given by the expression:

$$Batt_{cap} = \frac{P_{load} * DA * DM}{Vbatt * DOD} \left(\frac{Ah}{day}\right) \quad \textit{(Equation 14)}$$

where, DA: Days of Autonomy, the following codes was used to implement the days of autonomy

DA =ROUND (COUNTIF (J2:J8760,"=0")/24/52*0.5,1). This computes the number of days of solar photovoltaic unavailability.

DM: Design Margin (this is a factor usually introduced by RE designers to account for some losses or balance the effects of unexpected circumstances, for example, load transients, poor maintenance, and discharge transients)

DOD: Depth of Discharge (this describes how deeply or a percent limit to which a battery can be discharged)

If $P_{pv} > P_{load}$ Battery charging

$$Batt_{SOC} = Batt_{initial\,SOC}\,(t-1) + P_{pv} - P_{load}\,(t)\; x\; BattEff \quad \textit{(Equation 15)}$$

If $P_{pv} < P_{load}$ Battery discharging

$$Batt_{SOC} = Batt_{initial\,SOC} - P_{load}\,(t)\; x \left(\frac{1}{BattEff}\right) \quad \textit{(Equation 16)}$$

Where $P_{pv} = Total\ power\ \ from\ solar\ PV$

$$Batt_{SOC} = Battery\ state\ of\ charge\ at\ time\ (t)$$

$$Batt_{initial\,SOC} = Battery\ state\ of\ charge\ at\ time\ (t-1)$$

$$P_{load} = Load\ demand$$

Minimum battery state of charge can be deduced by multiplying the battery nominal capacity by the battery depth of discharge, and subtracting the result from the nominal capacity.

In this study, the equation used for hydrogen generation is based is given by the following;

$$mH_2 = \frac{P_{excess} * \eta_e}{39{,}400} \left(\frac{kg}{h}\right) \quad \textit{(Equation 17)}$$

$$\text{Where } mH_2 = \text{mass of hydrogen produced,}$$

$$\eta_e = \text{electrolyser effiecncy,}$$

$$P_{excess} = \text{electrolyser input power (W),}$$

The excess power produced by the PV panel is compared with the nominal power capacity of the electrolyser. All excess power that falls below the capacity will be utilised to generate hydrogen. The higher heating value (HHV) which describes the energy content of hydrogen (147000 kJ/kg = 39400 Wh/g) is used in the above equation. The electrolyser efficiency was modelled based on the following illustrations.

$$Efficiency\ (\%) = \left\{\frac{HHV\left(\frac{kWh}{kg}\right)}{E\left(\frac{kWh}{kg}\right)}\right\} * 100 \qquad (Equation\ 18)$$

$$E\left(\frac{kWh}{kg}\right) = \frac{P_{Max}}{(H_{2Mas}\ (\frac{kg}{h})} \qquad (Equation\ 19)$$

Where E = energy consumed, HHV = Higher heating value of hydrogen (39.4kWh/kg). This considers the electrolyser energy consumption per hydrogen mass flow rate.

2.0 Model evaluation

It has been estimated that more than 90% of the rural population in the sub-Saharan Africa relies on fuelwood and charcoal for cooking (IEA 2014). The software developed here allows for a low-carbon sustainable alternative based on hydrogen. For simulation purposes, a rural household in Nigeria has been considered for evaluating this tool. In this prototype model, cost implications are considered. As reported in Tracka in 2014, the household is in Okenkwu-Ebunwana village in Afikpo South LGA of Ebonyi state south-eastern Nigeria.

2.1 Solar energy resources

The village is located at latitude 5°58'N and longitude 7°52'E. According to sources investigated, the average daily energy requirement per household in rural Nigeria is 1.5kWh/d (597kWh/annum) (Adeoti, Oyewole, Adeboyega 2001). In Nigeria, rural households noncooking energy consumption is relatively low; villagers mostly need energy for lighting and entertainment devices such as radio or cassette players and television. The village terrain considered in this study is notable for its hilly and near inaccessible nature, has a low mean altitude of about 107m above sea level, and average annual rainfall of 198cm, as listed in (Vanguard Nigeria Newspaper, 2013). It is a tropical monsoon climate exposed to daily long hours (8 -10 hours) of sunshine throughout the year and receives on average a 4.7kWh/m^2/day of solar irradiation (Igweonu, Joshua and Eguzo 2011), ideal for solar power system utilization. **Figure** 1 shows the average monthly solar irradiation at Okenkwu village assuming a 10^0 - tilt angle as derived from hourly irradiation data obtained from an external source, (Meteonorm website). The mid-year dip corresponds to the rainy season. However, it is also possible to use a model – based approach to obtain the solar resource as demonstrated in (Šúri, Marcel, Thomas A. Huld, and Ewan D. Dunlop 2005).

Figure 1. Average monthly solar irradiation at horizontal surface, adjusted for 10-degree tilt.

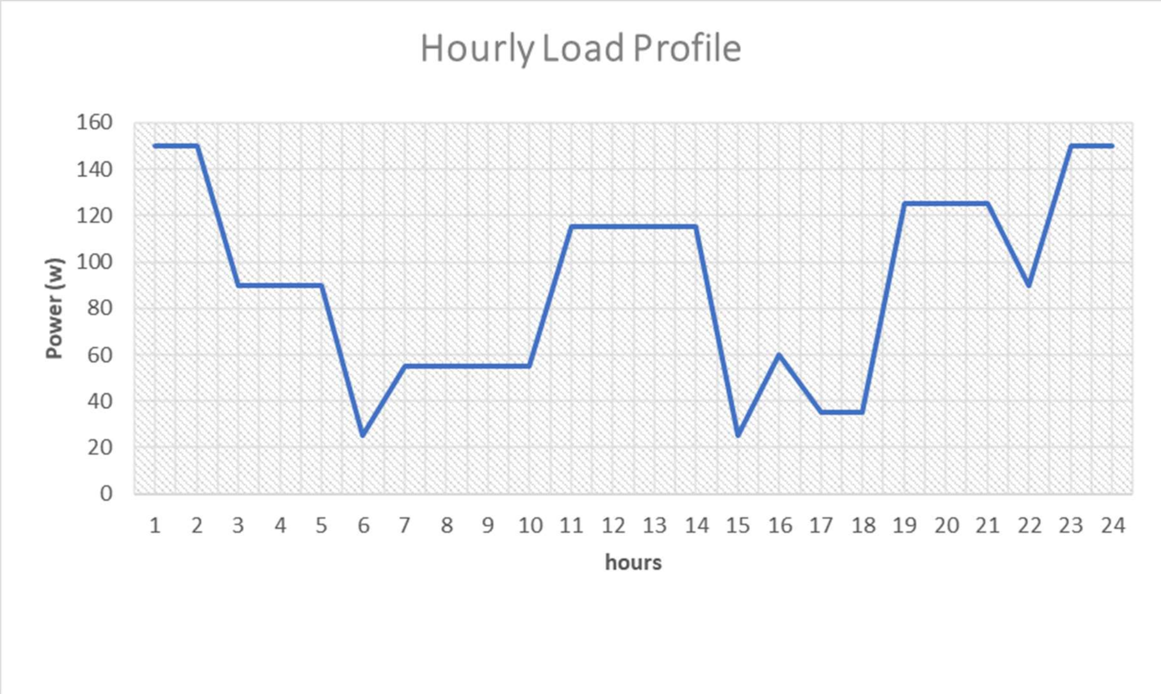
2.2 Load profile model

A single dwelling load demand model has been generated to determine the appropriate sizing of the photovoltaic panels, battery storage, and other auxiliary components that will be used in the design process. **Table 1** models the typical load characteristics by appliance type

Appliance	Number in use	Power (W)	Total Power (W)	Hours of use	Energy (Wh/day)
LED lighting	6	15	90	11	990
Radio set	1	25	25	11	275
Television	1	35	35	6	210
Table fan	3	20	60	8	480
Phone	3	10	30	8	240
Total	**12**	**105**	**200**	**44**	**2195**

[Table 1. Load profile illustrating the daily power requirements for a typical off-grid rural dwelling].

All power ratings of appliances used in this study are based on the consumption table provided at (ABS Alaskan, accessed Nov 2016). **Figure 2** illustrates the distribution of the daily load demand, with an assumption that this does not vary significantly throughout the year. Under this daily loading, the energy demand is 2.195kWh/day.



[Figure 2. Daily load demand profile for a household in Okenkwu village].

3.0 System Simulation

In the sizing process, it is a requirement that the components (PV and storage system) must provide sufficient energy to match the demand profile, through the rainy season when solar resources are low. This stipulation leads naturally to an oversizing of capacity during periods of high irradiance. Ideally this excess potential power should be generated and utilised. In this paper this is accomplished by incorporating a hydrogen generation facility as will be described below in 3.2.

Table 2 lists the cost specifications used in the optimisation process. It was assumed that the operating and maintenance costs of PV was zero percent of capital cost at a 5% return rate, and the batteries at 10% of capital cost. The PV and battery lifetimes were assumed at 25 years and 10 years respectively.

COMPONENTS	CAPITAL COSTS ($)	REPLACEMENT COST ($)
Solar PV	3236/kW	3236/kW
Battery	180/kW	170/kWh

[Table 2. Summary of costs components used in the optimisation].

3.1 Simulation Results

These data were input into SOHYSIMO and the optimum sizes and costs obtained is shown in the screenshot of **Figure 3**. **Figure 4** summarises the system annual performance. For optimum supply the system requires to be oversized by 623 kWh/annum. With an annual PV energy yield of 1557 kWh this represents a potentially wasted 40% of the available energy. For clarity the data in **Figure 4** is reproduced in **Figure 5** to illustrate the energy flow processes between the system elements. Demand and supply matching are important in an energy system, as we have seen in this simulation, the energy delivered to the battery is observed to be larger than that discharged from it.

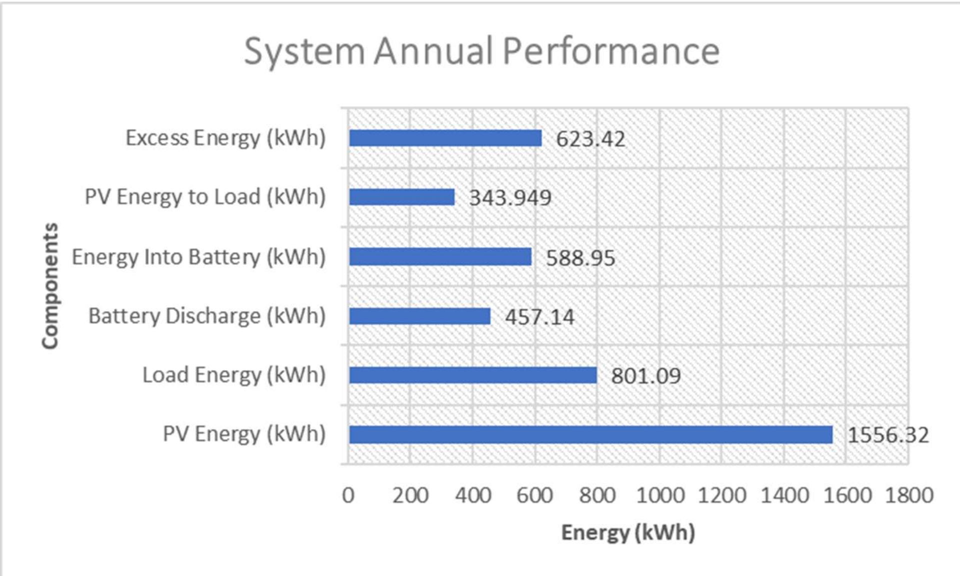
Next section presents the cooking demand calculation for the selected household to determine whether the available excess energy will be enough to generate hydrogen that can be used to satisfy the household's cooking requirement.

In simple off-grid PV/battery systems the overproduction described above would not normally occur; when the batteries are full and renewable power exceeds demand the PV will not have any additional loads to satisfy, and the output will be limited by the effective impedance. The introduction of an electrolyser provides an effective outlet for the excess energy (in this case 623kWh/annum).. Effectively the electrolyser provides a second storage medium in the form of hydrogen, and this can be recovered electrically through a fuel cell or used directly in its combustible form. This latter is a more efficient, cheaper and cleaner option if the hydrogen is used to displace traditional fossil fuels used in cooking.

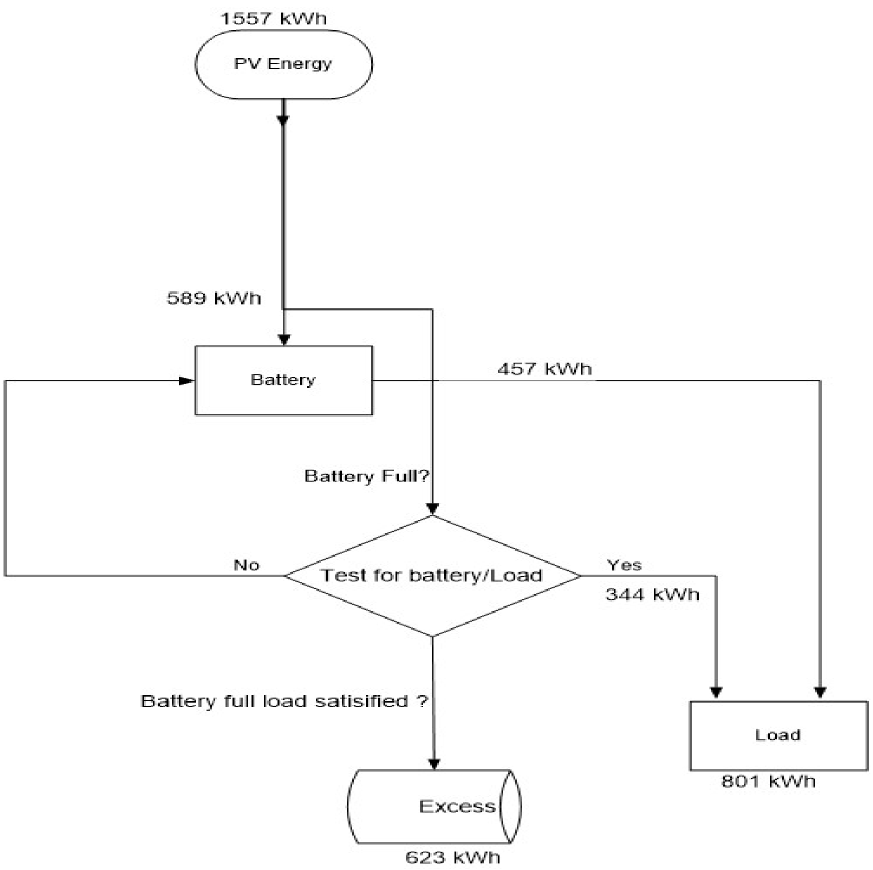
OPTIMISATION RESULTS

#	PV (kW)	Batt. (kWh)	Elec. (kW)	Init. Cap. Cost ($)	O&M ($/Yr)	Total NPC ($)	CH2 ($/kg)	LCOE ($/kWh)
1	1.2	3.7	0	4546	50.5	5262.5	0	0.3

[Figure 3. Optimisation results showing the system sizes that satisfies the specified electrical loading].



[Figure 4 . System annual performance].



[Figure 5 here. Energy flow process].

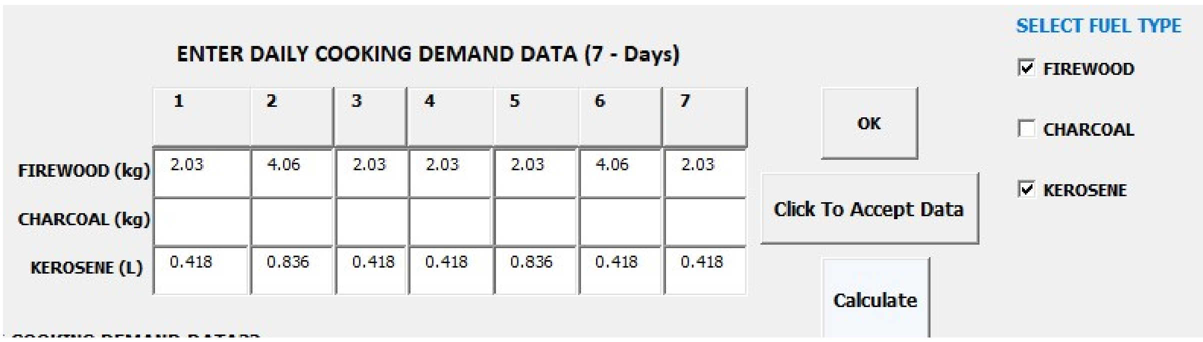
3.2 Obtaining the Cooking Demand

The two most conventional sources of fuel for domestic cooking in rural Nigeria are kerosene and firewood (Sepp 2014; The Nation Newspaper 2014). A publication in 2017 by the WHO, as reported by (CCAC secretariat 2017) estimated that 95,000 Nigerian women die each year because of indoor cooking with firewood. Providing the villagers access to a clean, sustainable means of cooking will significantly reduce deforestation and proffer the villagers a more dignified existence. In Nigeria, in 2015, it was reported that the daily firewood consumption is about 72,633 cubic meters (MacDicken et al. 2015), which corresponds to about 0.29kg per capita per day. In 2006, it was estimated that the household kerosene consumption in Nigeria was about 0.398l/day (Anozie et al. 2007). For this study this was converted by multiplying with an assumed factor of 1.05, to reflect an increase in cooking demand and gives a 0.418l kerosene consumption per day per household. These all depends on the level of income in the household. Those who income level fall below $1/day may prefer to use the kerosene only for lighting because of the costs and rely totally on firewood for cooking, as noted in Reuters article on June 2 2014 (Reuters Thomson Foundations 2014). **Table 3** lists the summary of daily cooking demand for a 7-person household in Nigeria rural area used in the current study, averaged at 1.9 kWh/day.

Fuel Type	**Energy density by mass**	**Demand per head**	**Demand per household**	**Stove efficiency (%)**	**Cooking demand (kWh)**
Firewood (air dry 20% MC*)	4.2 kWh/kg (APS 2018)	0.29 kg	2.03 kg	12	1
Kerosene	10.4 kWh/l (SWWR 2009)	0.059 l	0.418 l	43	0.86
Total					**1.9**

[Table 3. Estimated daily cooking demand for a typical rural 7- person household in Nigeria].

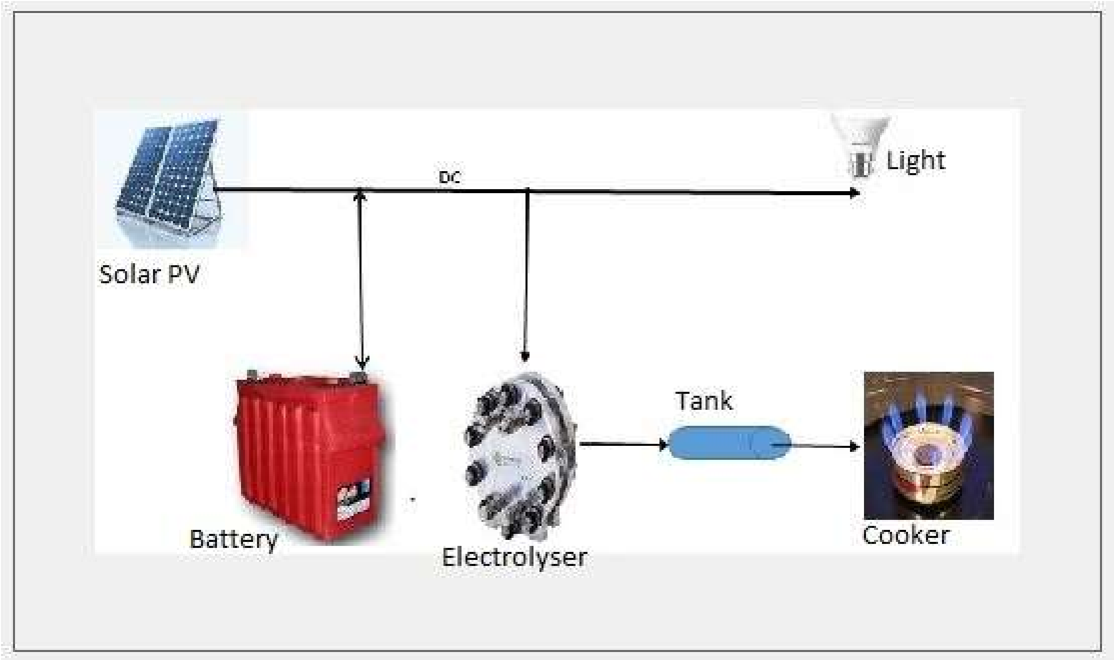
In **Figure 6** an estimate of the weekly cooking load is tabulated, based on the data in **Table 3**, and allowing for some variation in the daily totals. The weekly profile is assumed constant throughout the year.



[Figure 6. Estimated weekly cooking demand for a typical 7 – person rural household in Nigeria]

3.2.1 Hydrogen Energy Optimisation

In this section, the optimal sizing that can supply the household's electric load and cooking load profile considered in this study is presented. The underlying algorithm is such that the selected components (PV and battery) must provide sufficient energy to meet both demands as desired, at minimal costs. In the process, the 1.2 kW PV and 3.7 kWh battery simulated in **section 3.1** will be optimised with an electrolyser (for hydrogen generation) to satisfy both cooking and electric load. **Figure 7** shows the solar hydrogen cooking system configuration from SOHYSIMO user interface. It should be noted that the optimisation facility in the developed tool has the capability to maximise or minimise the system sizes to achieve this. If the excess power is not enough to satisfy both loads the tool increases the capacity to suit. Based on 2018 figures, it is assumed that the cost for the electrolyser is $1000/kW and the operating and maintenance cost is 10% percent of the capital cost. The expected lifetime is assumed at 15 years.



[Figure 7. Hydrogen cooking system configuration]

3.2.2 Results and Discussion

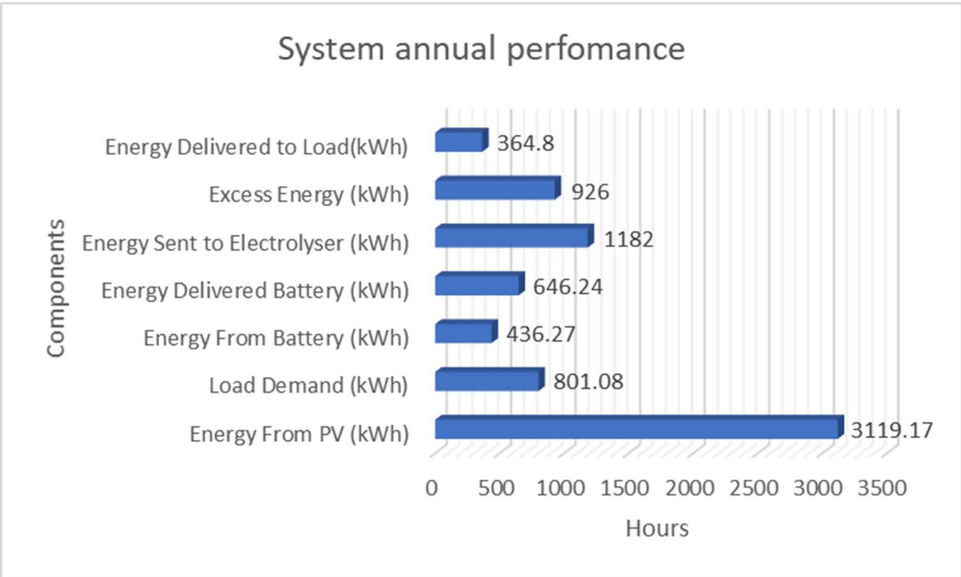
After optimisation, the optimum sizes obtained from SOHYSIMO that satisfies both the electrical and cooking loading were 2.42 kW PV, 0.6 kW electrolyser and 3.7kWh battery, assuming a maximum allowable depth of discharge of 50%**.** This data is summarised in **Table 4**.

Components	Capacity
Solar PV	2.42 kW
Battery	3.7 kWh (50 % DOD)
Electrolyser	0.6 kW

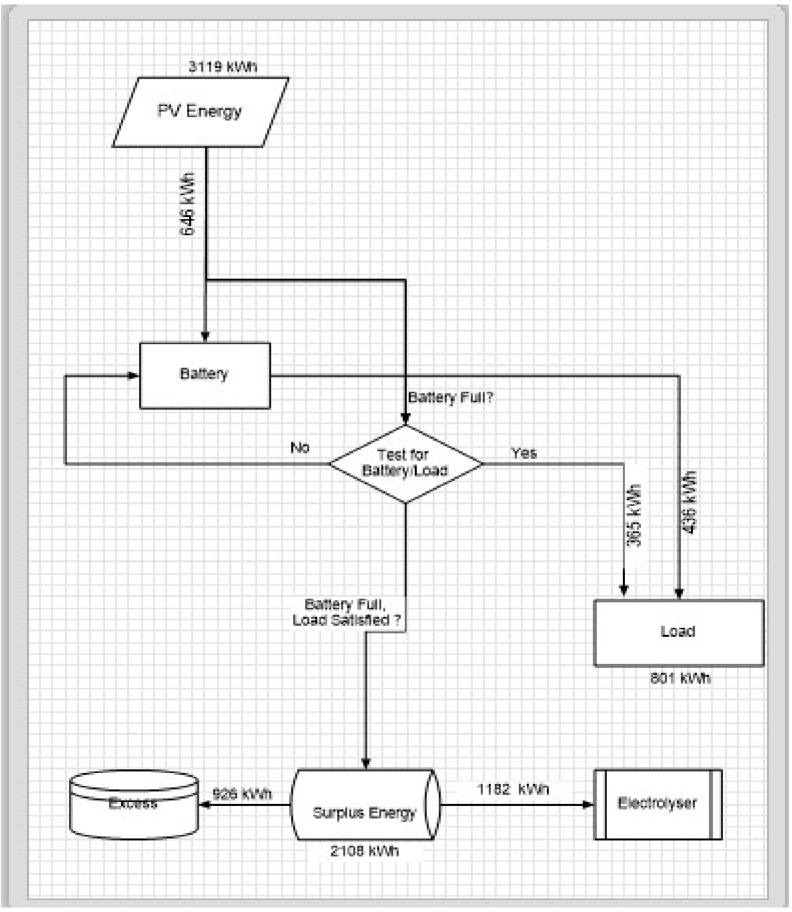
[Table 4. SOHYSIMO optimised component sizings].

The simulated and optimised system annual performance data is summarised in **Figure 8,** and the energy flow process is shown in **Figure 9**. From this optimisation result the total surplus (electrical) energy is 2,108 kWh. After meeting the thermal load an excess of 926 kWh is still available for utilisation.

This apparent mismatch of supply and demand over a protracted period is characteristic of most off-grid systems and relates to the dynamic relationships between inputs and outputs. It can be at least partially resolved through increased storage, or by introducing demand-side measures (for example water heating), but increased costs and complexity may reduce the overall cost-effectiveness.



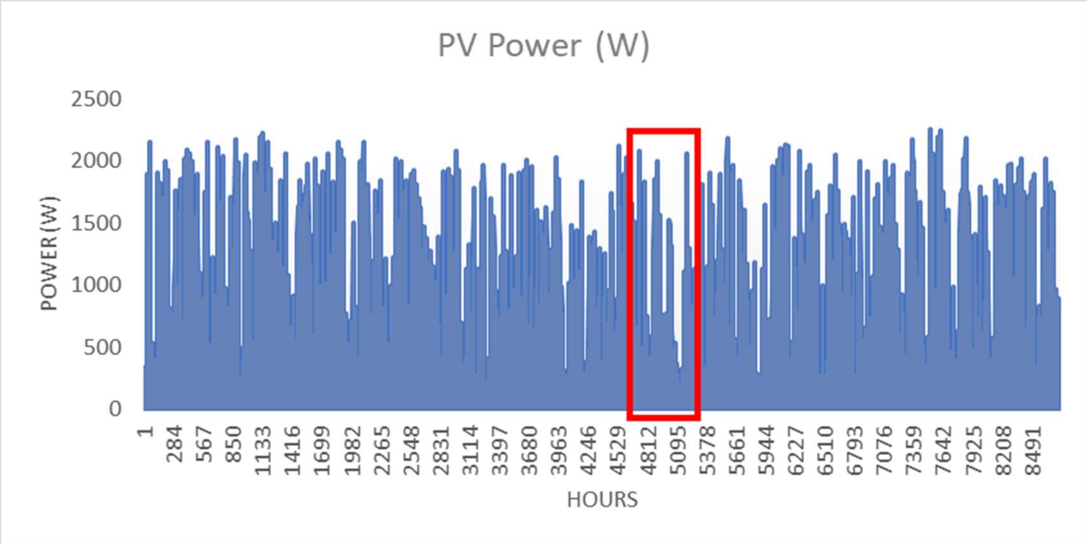
[Figure 8. System annual performance].



[Figure 9. Annual energy flow processes. To satisfy the cooking load 1,182kWh is required for hydrogen production].

4.0 System Annual Characteristics

In **Figure 10** the expected annual power production of the 2.42 kW PV array is displayed. The PV performance relates directly to the solar irradiance, and this shows reasonable uniformity as expected for a tropical climate. The exception is the highlighted area between the second and third quarter of the year, which coincides with the rainy season. It is this seasonal dip which is largely responsible for the system "oversizing" required to satisfy the demand in this period.



[Figure 10. Annual modelled output power of an unrestricted 2.42 kW PV array. The highlighted section illustrates the rainy season variability when the system will be under most stress].

With excess electrical energy being directed to the electrolyser the annual hydrogen production can be plotted as shown in **Figure 11**. Over the year period, the total generated hydrogen was 22.5 kg. Although the production rate appears linear, closer inspection reveals a drop in the summer months. To better visualise this the data is replotted in **Figure 12**, together with the PV energy production data**.** The average monthly PV power peaked at 0.39 kW in January, February, March, and December, with the lowest value at 0.29 kW in July. The strong correlation between seasonal PV variations and hydrogen production are expected with the system hierarchy as chosen.

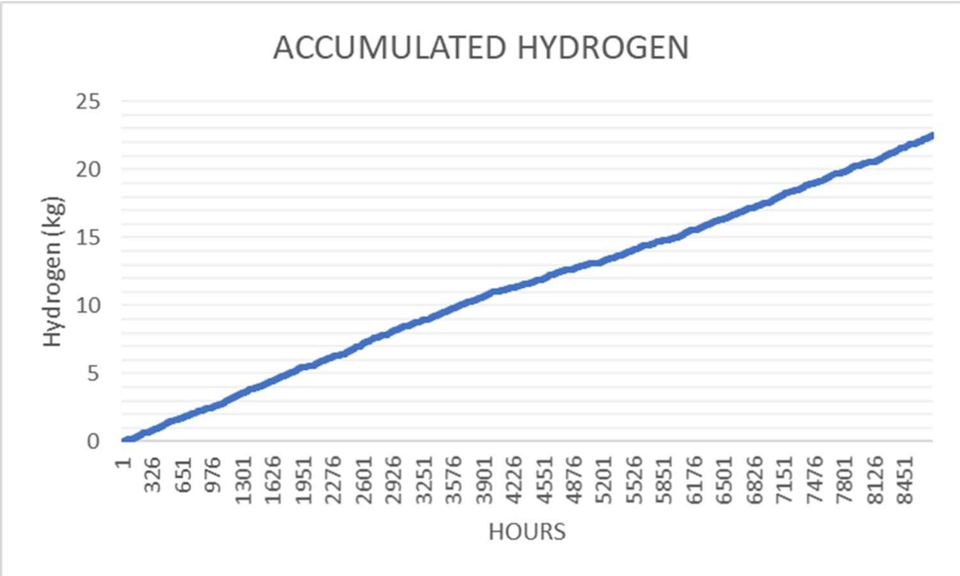
Due to the smallness of the size of the selected electrolyser (0.6 kW), it was unable to utilise all the surplus. However, the developed tool contains a facility whereby the software suggests a larger electrolyser size that can utilise all the surplus energy, for optimality. In order to improve the efficiency of the hydrogen production process, it has been recommended that electrolysers should be operated based on minimum input power (20% of rated capacity).

This represents the minimum input power required for the electrolyser to start. For this reason, the 0.6 kW electrolyser could not utilise all the surplus energy, as it produces hydrogen based on the minimum input power. The hourly hydrogen production was also plotted for clarity; **Figure 13** shows the hourly hydrogen generated over the year period simulated. The hydrogen produced peaked at 11 g/hour with visible spread of variations and fluctuations which are linked to both the solar irradiation levels and to the load profile. The red ring highlights those periods of low solar irradiations, as hydrogen production correlates with the amount of energy input from the solar PV (as already shown with a red ring in **Figure 10**. It can be seen that hydrogen production was restricted at 11 g/hr all year indicating that the electrolyser was being operated below its capacity, and that a larger electrolyser would produce more hydrogen.

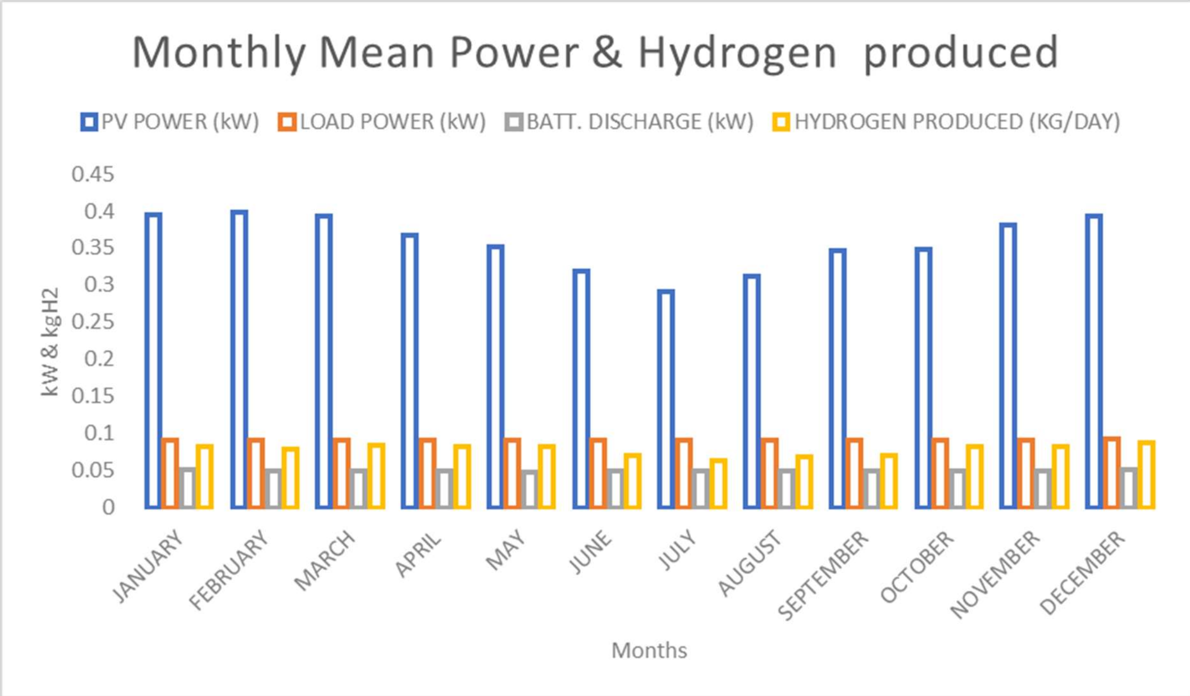
It has been recommended that, hydrogen be stored in such a way that it could occupy a smaller volume as efficiently and conveniently as possible for future use. However, there is a tension between compactness of storage and system efficiency associated with compression processes. The most commonly employed method of hydrogen storage is as a compressed gas (the simplest method). Other methods of hydrogen storage are solid storage – in metal hydrides, and cryogenic hydrogen storage – liquid hydrogen. Hydrogen has a poor energy density by volume (0.08988 g/l in gaseous state, i.e. 7 % of the density of air; 70.8 g/l as liquid (at 253°C), i.e. 7% of the density of water; and 70.6 g/l as solid (-262°C). Therefore, it must be compressed to very high pressures to store a sufficient amount of hydrogen for many practical applications. Usually compression of hydrogen gas is carried out in multiple stages with the first stage providing a pre-pressurisation from 1-atm to several atmospheres. In this process, the pressure level can be selected based on the maximum permitted pressure the storage tank can withstand but is relatively energy intensive. Researchers have demonstrated that the energy required to detach 1kg of hydrogen is 26,801 Ah (Göllei, Attila, Péter Görbe, and Attila Magyar 2016). High-pressure hydrogen is stored in thick-walled tanks (mainly of cylindrical or quasi-conformable shape) made of high strength materials to ensure durability. To determine the size of the storage system (or container/tank) required in cubic meter as previously explained, we start by converting kilogram hydrogen to cubic meter of hydrogen thus;

1 kg H_2 = 11.13 m^3 (gas at s.t.p).

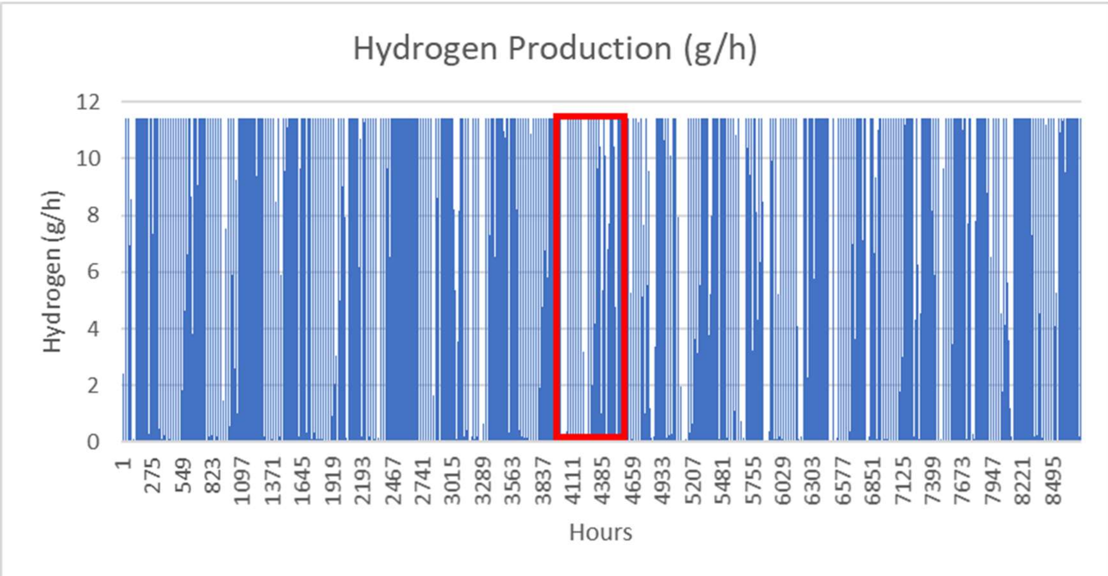
22.5 kg H_2 = 11.13 m^3/1 kg x 22.5 kg = 250 m^3. Therefore, if this is stored at 30 bar pressures, perhaps with a pressurised electrolyser, it follows that the size of storage volume required is 8.3 m^3.



[Figure 11. Accumulated hydrogen production of 600W electrolyser over a year period.]



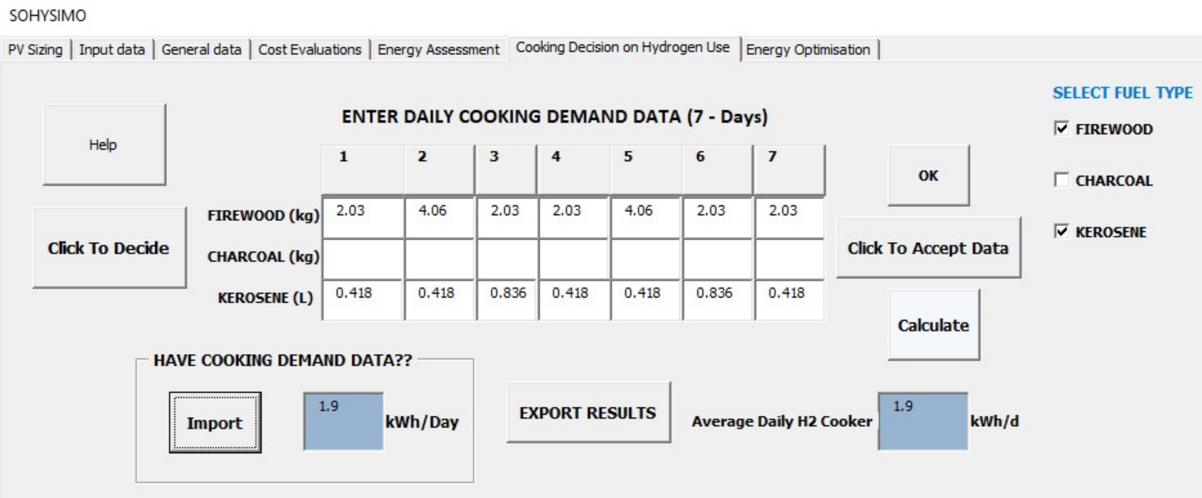
[Figure 12. System monthly performance.]



[*Figure 13*. Annual hydrogen production (600W electrolyser) in grams/hour. The highlighted area corresponds to a period of low electrical supply to the electrolyser. The maximum output of 11 g/hr corresponds to fully loading of the electrolyser.]

4.1 Cooking Computation

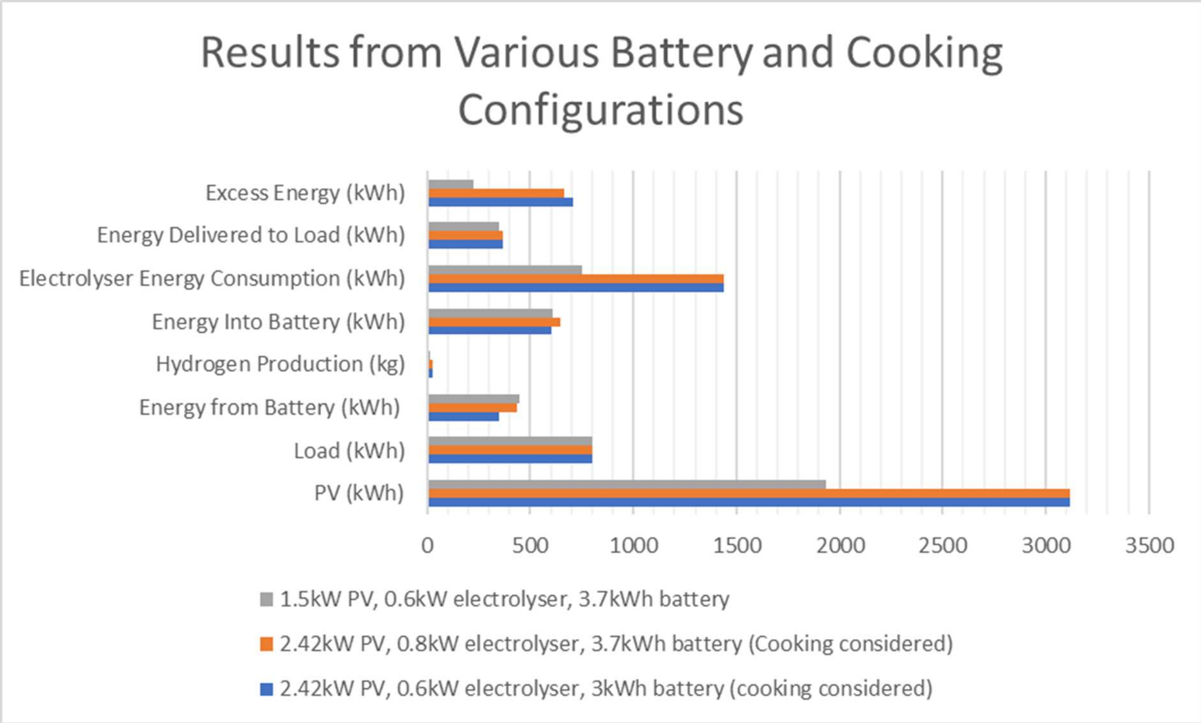
The hydrogen produced was utilised in the hydrogen cooker to meet the domestic cooking demand of the rural household. After computation, the daily energy available from the hydrogen cooker was 1.9 kWh/day, while the daily average cooking demand was 1.9 kWh/day as shown in **Figure 14**. Interestingly, the H_2-cooker could not meet the cooking demand for a total of only 5 days over the year, which can be attributed mostly due to the limited size of the electrolyser, as previously highlighted. For any off-grid system there will be a tension between the desire for 100% supply and with system oversizing, and 5 days of shortfall represents a good outcome.



[Figure 14. SOHYSIMO hydrogen cooking page showing the cooking demand input and the computed energy available from the hydrogen cooker.]

4.2 Energy System Size Variations

To test the effects of a larger and smaller component sizes on the system, a set of simulations were run with various sizing options tested, by varying the cooking load and keeping the original electric load profile constant. **Figure 15** shows the results obtained from the simulation for different configurations considered, and **Table 5** lists the cost variations. It was found that to effectively meet the cooking load, a larger PV and electrolyser is required; with a 1.5 kW PV and 0.6 kW electrolyser arrangement, the H_2-Cooker could not meet the cooking demand but satisfied the electric load. However, with a 2.4 kW PV and 0.8 kW electrolyser and 3.7 kWh battery arrangement, a 100 % supply was realised. In **Table 5,** it is evident that an increased PV and electrolyser size may result to a lower cost per kilogram of hydrogen produced. A $22/kg H_2 was seen in the configuration that integrates a 2.42 kW PV and 0.8 kW electrolyser, and 3.7 kWh battery. This is 45% and 19% lower when compared to $40/kg and $27.2/kg of the other two configurations. The NPC is 3.65% higher at $10,504 when compared to the configuration with closest cost performance at $10,134. The levelised cost of energy (LCOE) seen in the three configurations tested are $0.6/kWh, $0.5/kWh, $0.5/kWh respectively. However, there is also the possibility of utilising the surplus energy in H_2-genset to meet the electric load. That is if we consider the fact that a petrol powered genset for electricity needs is prevalent in the rural areas of Nigeria; hence, the household used in this study would probably have one, and this may be rebuilt to a hydrogen powered genset as demonstrated by (Ulleberg, Nakken and Ete 2010).



[Figure 15. Graph showing the simulation results obtained from various configurations tested.]

Configurations	NPC ($)*	Project Initial Cost ($)	LCOE ($/kWh)**	H_2 Cost ($/kg)
1.5kW PV,0.6kW electrolyser, 3.7kWh Battery	7865.89	6121	0.6	40
2.42kW PV, 0.8kW electrolyser, 3.7kWh Battery (cooking considered)	10504.1	9289	0.5	22
2.42kW PV, 0.6kW electrolyser, 3.7kWh Battery (cooking considered)	10134	9172	0.5	27.2

*Net present cost

**Levelised cost of energy

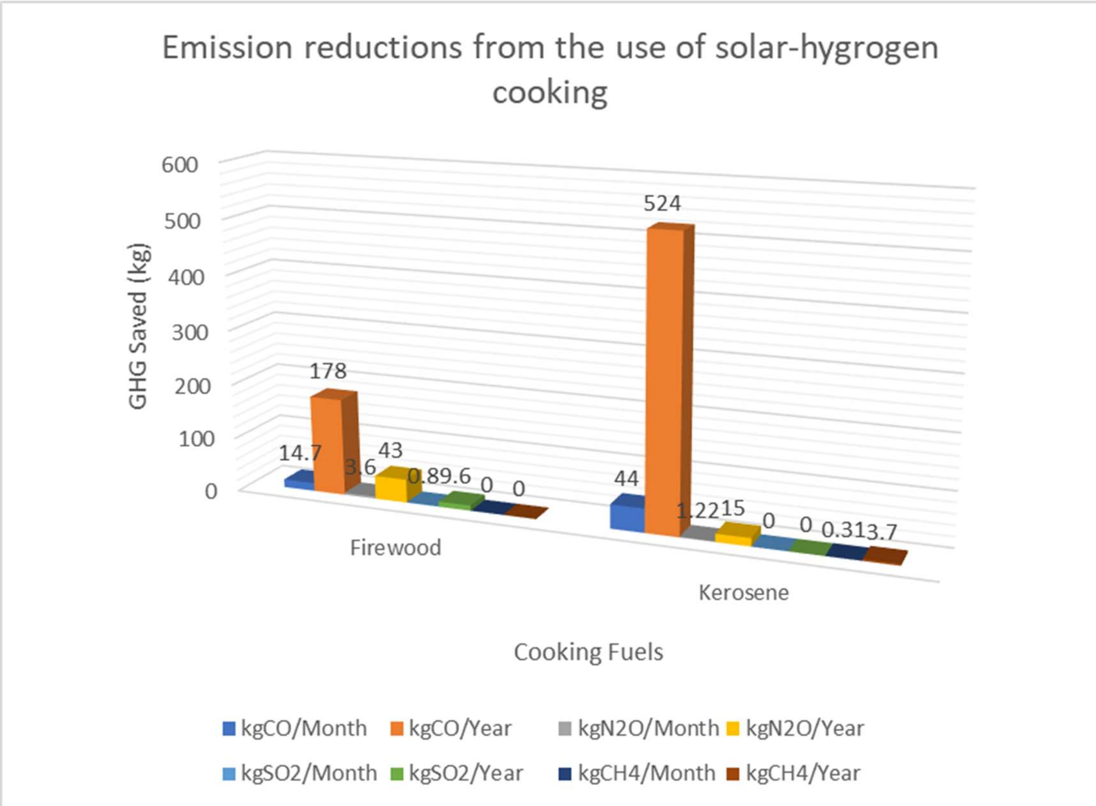
[Table 5. Cost variations for three various system configurations tested.]

5.0 Environmental Impact Assessment and Emission Reductions

The climatic consequences of greenhouse gas (GHG) emission into the atmosphere has been recognised globally. The two main components that make up 'Solar – Hydrogen Cooking' are solar PV and hydrogen gas produced using an electrolyser, and these are free from operating emissions, as already noted. The continued use of energy - inefficient and unsustainable cooking stoves in the low and middle income rural areas of the developing countries has a recognised harmful effect on the health and wellbeing of the people. Cooking and lighting with kerosene and/or firewood emits substantial amounts of carbon – dioxide (CO_2), carbon mono – oxide (CO), sulphur oxide (SO_2), Nitrous –oxide (N_2O) and methane (CH_4) into the atmosphere. Firewood used for cooking in these rural households is usually sourced from local forests, and the adverse effect of this practice is unregulated deforestation. It has been estimated that about one-third of all CO_2 released into the atmosphere today is caused by deforestation (Lam et al. 2012). Now, to compare the benefits of providing the rural household with a sustainable means of cooking. For kerosene consumption, the household would consume approximately 16.7 litres (equivalent to 3.5 gallons at 0.54 litre per day by averaging the 7 -day kerosene demand) per month.

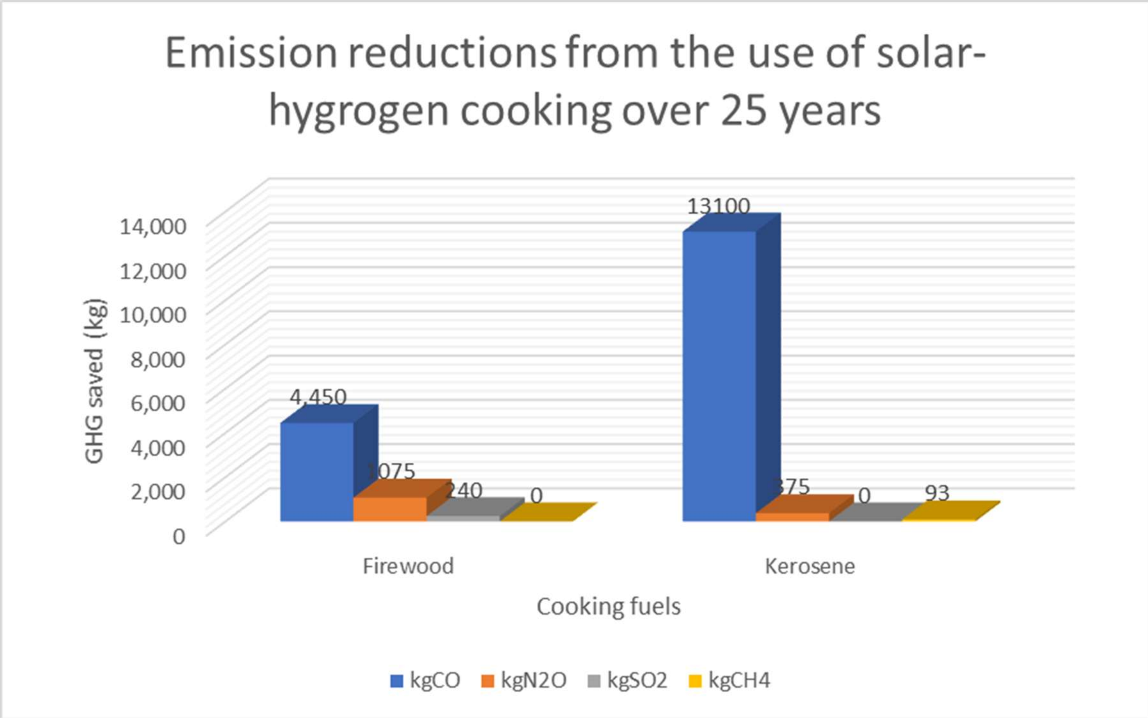
5.1 Impacts of Kerosene and Firewood Burning

According to reports, the CO_2 emission factor for kerosene burned is 2.61kg per litre (Mishra 2009). Similarly, for other greenhouse gases e.g. N_2O and CH_4, the emission factors of these relating to kerosene are 0.0731kg/L and 0.0183kg/L respectively. GHG emissions are calculated as a product of the amount of fuel, its energy density and the emission factor. A study in Nigeria has shown that the firewood emission factors for GHG; CO, N_2O and SO_2 are 181.84g/kg, 44.7g/kg and 9.87g/kg respectively (Adeniji et al. 2015). To estimate the GHG emission savings from these unsustainable fuels, we can consider the quantity of kerosene and firewood burned per household. The daily average firewood and kerosene requirements for the 7 – person household considered in this study are 2.61 kg and 0.54 L respectively. This translates to 81 kg firewood and 16.7 L kerosene per month or 972 kg firewood and 200 L kerosene per year. With these emission factors, we obtain the annual GHG emission savings from these (firewood and kerosene) are 178kgCO, 43kgN_2O, 9.6kgSO_2 and 524CO, 15kgN_2O and 3.7kgCH_4 as shown in **Figure 16**.



[Figure 16. Green House Gas (GHG) emission saved from solar hydrogen cooking.]

Figure 17 shows the amount of GHG that could be saved over a 25- year lifetime of the solar – hydrogen system, by reduction in the use of kerosene and firewood as cooking fuels. Interestingly, for carbon-monoxide, savings from reduction in kerosene use is higher at 13,100kg compared to firewood at 4,450kg, and this shows the fact that fuels derived from hydrocarbons constitute more emission than that from burning biomass.



[Figure 17. GHG that could be saved over a 25- year lifetime of the solar – hydrogen system, by reduction in the use of kerosene and firewood.]

6.0 Conclusions

The aim of this study was to develop a simulation tool for solar-hydrogen energy system which addresses both electrical and thermal (cooking) needs. This is a unique approach in modelling a solar PV based hydrogen production and utilisation and presents an excellent opportunity for designers who may find this application useful. The tool was used to simulate the energy assessment of a seven-person rural household in Nigeria. It has been shown that there is a great opportunity in generating electricity from renewable sources, especially when it is properly sized. It has been shown that excess energy that will be generated can be made utilised to produce hydrogen, and that it may be advantageous for both efficiency and health reasons to use the hydrogen produced for domestic cooking rather than increased storage. Operating and maintenance costs are an important factor in every renewable energy-based project, and a novel method for calculating this has been developed and incorporated into the model to obtain an optimal design of a solar PV-hydrogen project. In future, the simulation capability of the developed software tool may be enhanced by including one or more renewable energy source, e.g. wind, and the solar radiation model may also be improved by adding a facility that can enable a user to access irradiation data via the internet; e.g. the NASA real time solar data. Future versions of SOHYSIMO will address the need for more sophisticated load modelling on a village scale and consider the trade-offs between component sizing and meeting of the cooking load in more depth. The enhanced cooking optimisation process adopted in this model has shown that it is possible to obtain an optimal configuration that will serve both the cooking load and electric load with minimal days of shortage of supply.

References

ABS Alaskan "Power consumption table" http://www.absak.com/library/power-consumption-table, Accessed 10/11/2016.

Adeoti, O., B. A. Oyewole, and T. D. Adegboyega. "Solar photovoltaic-based home electrification system for rural development in Nigeria: domestic load assessment." *Renewable Energy* 24, no. 1 (2001): 155-161.

Adeniji, B. A., G. R. E. E. Ana, B. O. Adedokun, and O. I. Ige. "Exposure to emissions from kerosene cooking stoves and the pulmonary health status of women in Olorunda community, Ibadan, Nigeria." Journal of Environmental Protection 6, no. 05 (2015): 435.

Ali, Mohammed Moanes E., and Sameer K. Salih. "A visual basic-based tool for design of stand-alone solar power systems." *Energy Procedia* 36 (2013): 1255-1264.

Anozie, A. N., A. R. Bakare, J. A. Sonibare, and T. O. Oyebisi. "Evaluation of cooking energy cost, efficiency, impact on air pollution and policy in Nigeria." *Energy* 32, no. 7 (2007): 1283-1290.

Akintola, Omigbodun. 2013 “Climate, Climate Change, the Dry and Wet Seasons in West Africa (2)”

Australian Petroleum Statistics (APS 2018) https://www.energy.gov.au/ government-priorities/energy-data/australian-petroleum-statistics Accessed 19/01/2018.

Barbir, Frano. "PEM electrolysis for production of hydrogen from renewable energy sources." *Solar energy* 78, no. 5 (2005): 661-669.

CCAC (2017) “Nigerian women taking bold action to reduce household air pollution” CCAC secretariat March 2017. http://www.ccacoalition.org/en/news/nigerian-women-taking-bold-action-reduce-household-air-pollution Accessed 10/11/2016.

Connolly, David, Henrik Lund, Brian Vad Mathiesen, and Martin Leahy. "A review of computer tools for analysing the integration of renewable energy into various energy systems." *Applied energy* 87, no. 4 (2010): 1059-1082.

Diaf, Said, Djamila Diaf, Mayouf Belhamel, Mourad Haddadi, and Alain Louche. "A methodology for optimal sizing of autonomous hybrid PV/wind system." *Energy Policy* 35, no. 11 (2007): 5708-5718.

Egun Sunday “Evil of kerosene” 2014 http://thenationonlineng.net/evil-kerosene-firewood Accessed 10/11/2016.

Göllei, Attila, Péter Görbe, and Attila Magyar. "Measurement based modeling and simulation of hydrogen generation cell in complex domestic renewable energy systems." *Journal of Cleaner Production* 111 (2016): 17-24.

IEA "Africa Energy Outlook: A focus on energy prospects in Sub-Saharan Africa. " World energy outlook special report, (2014) http://www.iea.org/publications/freepublications/publication/WEO2014_AfricaEnergyOutlook.pdf Accessed 25/05/2017.

Igweonu, E.I., Joshua, R.B. and Eguzo, C.V. "Solar collector efficiency, analysis and application." Continental J. Engineering Sciences 6, no.1 (2001)24 – 30.

Kayode Ogunbunmi, Madalitso Mwando (2014) "Africa's climate policies burned by firewood dependence" Thomson Reuters Foundation, June 2014. http://news.trust.org/item/20140530183509-63ekq/ Accessed 10/11/2016.

Kuo, Yeong-Chau, Li-Jen Liu, Wei-Hsiang Tung, Yi-Ming Huang, and Su-Hau Ho. "Smart Integrated Circuit and System Design for Renewable Energy Applications." In *2012 International Symposium on Computer, Consumer and Control*, pp. 377-380. IEEE, 2012.

Lam, Nicholas L., Kirk R. Smith, Alison Gauthier, and Michael N. Bates. "Kerosene: a review of household uses and their hazards in low-and middle-income countries." Journal of Toxicology and Environmental Health, Part B 15, no. 6 (2012): 396-432.M.P Mishra (2009) ICSE environmental education, class x. S.Chand publishers New Delhi.

MacDicken, K., Ö. Jonsson, L. Piña, S. Maulo, V. Contessa, Y. Adikari, M. Garzuglia, E. Lindquist, G. Reams, and R. D'Annunzio. "Global Forest Resources Assessment 2015: how are the world's forests changing?." (2016).

Mark, C, Georgina,O, James, T, Guy, S, Lain, S. 2015. "Safety Issues Surrounding Hydrogen as an Energy Storage Vector" http://www.igem.org.uk/media/361886"/final%20report_v13%20for%20publication.pdf Accessed 10/11/16.

Meteonorm software programme; http://www.meteonorm.com/

Mhalas, Amit, Mohamad Kassem, Tracey Crosbie, and Nashwan Dawood. "A visual energy performance assessment and decision support tool for dwellings." *Visualization in Engineering* 1, no. 1 (2013): 7.

Onwe Christian A., 2017. "Modelling and assessment of renewable energy systems for remote rural areas in Nigeria." PhD Thesis., The University of Dundee United Kingdom.

Sepp, S., "Multiple-household Fuel Use: A Balanced Choice Between Firewood, Charcoal and LPG" BMZ, Federal Ministry for Economic Cooperation and Development 2014.

South West Woodland Renaissance (SWWR 2009) "A guide to small-scale wood fuel (biomass) heating systems." Forestry Commission England. https://www.cse.org.uk/pdf/guide%20to%20small-scale%20wood-fuelled%20heating.pdf Accessed 19/01/2018.

Šúri, Marcel, Thomas A. Huld, and Ewan D. Dunlop. "PV-GIS: a web-based solar radiation database for the calculation of PV potential in Europe." *International Journal of Sustainable Energy* 24, no. 2 (2005): 55-67. "

Topriska, Evangelia, Maria Kolokotroni, Zahir Dehouche, and Earle Wilson."Solar hydrogen system for cooking applications: Experimental and numerical study." *Renewable Energy* 83 (2015): 717-728.

Tracka "Extension of electricity to Okenkwu Ebunwana in Afikpo South LGA of Ebonyi state" http://www.tracka.ng/issues/view/268 Accessed 10/11/2016.

Ulleberg, Øystein, Torgeir Nakken, and Arnaud Ete. "The wind/hydrogen demonstration system at Utsira in Norway: Evaluation of system performance using operational data and updated hydrogen energy system modeling tools." International Journal of Hydrogen Energy 35, no. 5 (2010): 1841-1852.

Vanguard News, February https://www.vanguardngr.com/2013/02/climate-climate-change-the-dry-and-wet-seasons-in-west-africa-2/" Accessed 10/11/2016.

Vladimir ÁČ, and Suchanek, J., "Expert system for design of off-grid renewable energy sources." University review, (8), No 3-4, (2014): 38-44.

Yilanci, A., I. Dincer, and H. K. Ozturk. "A review on solar-hydrogen/fuel cell hybrid energy systems for stationary applications." Progress in Energy and Combustion Science 35, no. 3 (2009): 231-244.